REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
4/21/06

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
5/27/05 – 1/31/06

4. TITLE AND SUBTITLE
A Multicell Trap for Positron Accumulation and Storage

5a. CONTRACT NUMBER

5b. GRANT NUMBER
HR0011-05-1-0041

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER DODAC HR0011

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Advanced Research
Projects Agency
Tactical Technology Office
3701 N. Fairfax Drive
Arlington, VA 22203-1714

10. SPONSOR/MONITOR'S ACRONYM(S)
DARPA

11. SPONSOR/MONITOR'S REPORT NUMBER(S) U590/00

12. DISTRIBUTION / AVAILABILITY STATEMENT

Unrestricted.

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT (Abbreviated for this form)

There has been considerable progress in accumulating positrons. The project described here begins a next major step in this area – development of a novel multicell Penning trap for large numbers of positrons. The long-range goal of this project is the development of a device to accumulate $N \geq 10^{12}$ positrons (i.e., an increase of a factor of 1000 over current performance) and to store this collection of antimatter as a plasma for times as long as weeks. The multicell trap apparatus will be a few cubic meters in volume and portable. The development of this device would be an important step toward the development of even more flexible, portable reservoirs of antimatter with few logistic requirements. The first phase of the project, for which this is the final technical report, used test electron plasmas to develop new capabilities to store large numbers of particles in a single plasma cell and to manipulate the resulting plasmas. The project developed a technique to move plasmas across the magnetic field, and to operate more than one plasma cell simultaneously. All five of the proposed tasks were accomplished. Two subsequent options, if approved for funding, would enable the design, construction, and testing of the stand-alone multicell positron trap, described above, to accumulate and store 10^{12} positrons.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Clifford M. Surko
a. REPORT	b. ABSTRACT	c. THIS PAGE	None	19	19b. TELEPHONE NUMBER *(include area code)*
~~All~~ U	~~All~~ U	~~All~~ U			858 534 6880

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

April 21, 2006

Final Technical Report

A Multicell Trap for Positron Accumulation and Storage

Grant No: HR0011-05-1-0041
ARPA Order No. U590/00
DODDAC: HR0011
(Project period: 5/27/05 – 1/31/06)

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Abstract

There has been considerable progress in accumulating positrons (i.e., the antiparticles of electrons) in Penning traps – devices specifically designed to confine plasmas of a single sign of charge using an arrangement of electric and magnetic fields. The project described here begins a next major step in this area – development of a novel multicell Penning trap for large numbers of positrons. The long-range goal of this project is the development of a device to accumulate $N \geq 10^{12}$ positrons (i.e., an increase of a factor of 1000 over current performance) and to store this collection of antimatter as a plasma for times as long as weeks. The multicell trap apparatus will be a few cubic meters in volume and portable. This reservoir of positrons could replace accelerator- or radionuclide-based positron sources, as necessary. It could also be used to provide bursts of positrons for a range of scientific and technological applications. The development of this device would be an important step toward the development of even more flexible, portable reservoirs of antimatter with few logistic requirements. The first phase of the project, for which this is the final technical report, used test electron plasmas to develop new capabilities to store large numbers of particles in a single plasma cell and to manipulate the resulting plasmas. The project developed a technique to move plasmas across the magnetic field, and to operate more than one plasma cell simultaneously. All five of the proposed tasks were accomplished. Two subsequent options, if approved for funding, would enable the design, construction, and testing of the stand-alone multicell positron trap, described above, to accumulate and store 10^{12} positrons.

1. Overview

Phenomena involving positrons (i.e., the antiparticles of electrons) are important in many fields of science and technology including astrophysics, plasma and atomic physics, and materials science [1-6]. Scientific applications include Bose-condensed gases of positronium atoms and the formation and study of antihydrogen (i.e., stable, neutral antimatter). Technological applications include the characterization of materials for chip manufacture. On a longer time horizon, potential applications include creation of an annihilation gamma-ray laser [7], energy storage, weaponry, and space propulsion. The principal impediment to pursuing many of these applications has been the inability to accumulate, cool and manipulate large numbers of low-energy positrons.

Recently, the P.I. and collaborators have made progress in accumulating antimatter and using these collections of antimatter in novel applications. The basic experimental apparatus for this research and the first stage of the project proposed here is shown schematically in Fig. 1. This Penning-Malmberg trap, as it is commonly referred to in the plasma literature, uses a uniform magnetic field and electrostatic potentials at each end of the trap to confine particles of a single sign of charge (e.g., positrons or electrons) [2, 8-10].

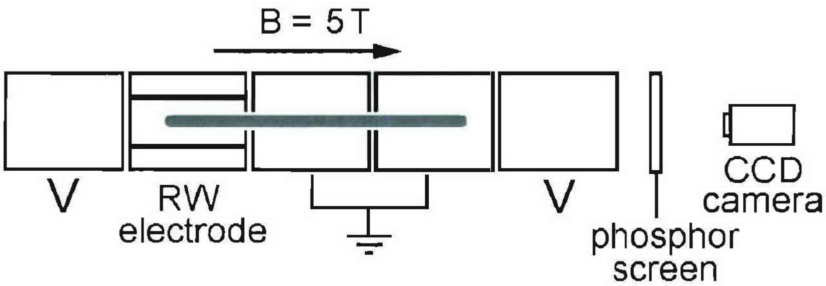

Fig. 1. Schematic diagram of a Penning-Malmberg trap. Also shown is a rotating-wall electrode that is used for plasma compression and a phosphor screen and CCD camera for imaging the radial density profile of the plasma. The actual device used for the work described here is illustrated in Fig. 3.

The work reported on here took the next steps in this research and development. The long-term goal is to increase by orders of magnitude the number of positrons that can be accumulated and stored for weeks. The basic strategy is to develop a device referred to here as a *multicell trap*, namely an assembly of 95 Penning-Malmberg traps arranged in a common magnetic field and common vacuum system.

The results of this research are expected to represent a major step toward the development of versatile, *portable antimatter traps* – decoupling the end use of the antimatter from fixed, intense sources of antiparticles such as accelerators or radioactive materials. Fig. 2 illustrates the objectives of the work proposed here in the context of the progress that has been made in positron trapping over the past two decades.

The research exploited the recent design proposed by the P.I. and collaborators for a novel, multicell Penning-Malmberg trap to maximize antimatter plasma confinement and storage capacity [11, 12]. The design divides the total number of stored antiparticles into many (e.g., ~ 95) plasma cells, separated by copper walls. These walls screen out the

space charge of the plasma, thereby reducing the required confinement voltages by an order of magnitude or more. The multicell design also increases the plasma confinement time, thereby greatly reducing the requirements for electrode and magnetic field uniformity. The long-term goal of the research and development is to create a flexible, multicell trap that can be used to accumulate and store $N \geq 10^{12}$ positrons for a week or more. The currently proposed plan to complete the design, construction and testing of a multicell trap for $> 10^{12}$ positrons is described briefly in Appendix I.

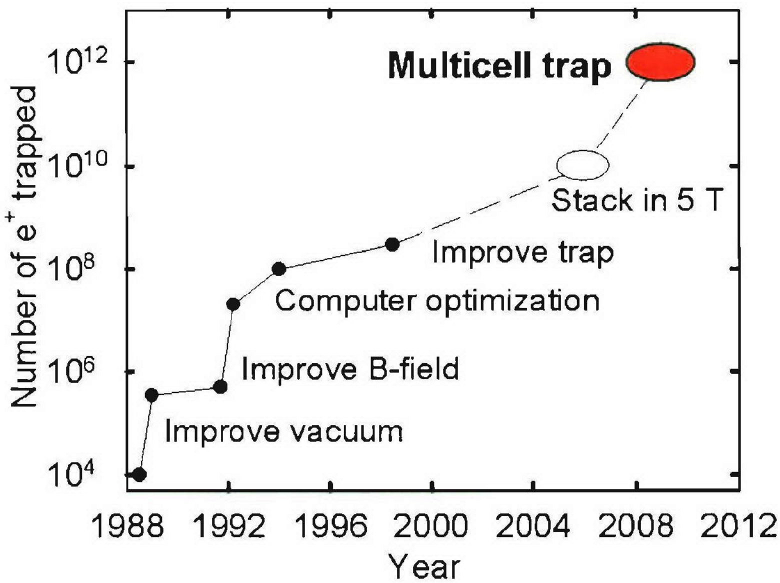

Fig. 2. Progress in positron trapping from similar strength sources (~ 100 mCi ^{22}Na) using a buffer-gas accumulator: actual, record results from the P.I. and collaborators (solid line), and projected results (dashed line). The projected value for the multicell trap is shown as the shaded oval.

The first phase of the project, for which this is the final report, completed R & D on tasks crucial to the construction of a multicell trap using existing apparatus. Electron plasmas were used in place of positrons for this work in order to increase the data rate. This work has allowed us to increase the cell electrical confinement potential from 100 to 1,000 V; increase plasma-cell storage capacity by an order of magnitude; begin the first multicell operation; and develop the ability to move plasmas off the magnetic axis in the 5 tesla magnetic field. Finally, a design was completed for the electrode structure that would be used in the next phase of the project, should funding for that phase become available. Success with each of these tasks constituted a separate deliverable.

2. Technical Background for the Project

2.1 Tools used in the research

The P. I. and collaborators have led the world developing methods to accumulate and manipulate positron plasmas. Two of these techniques, and key pieces of apparatus from this research are central to the research described here.

Buffer-gas positron accumulator. Positrons are accumulated in a specially designed Penning-Malmberg trap, which confines a cylindrically shaped plasma using a uniform magnetic field and electrostatic potentials at the ends [13]. The positron plasma cools to room temperature in ≤ 0.1 second and can be confined for hours. The trapping efficiency, 25%, is more than an order of magnitude larger than any other technique developed to date. Typically $N \sim 3 \times 10^8$ e^+ can be accumulated from a 100 mCi ^{22}Na radioactive source and noble gas moderator in a few minutes, and stronger positron sources are currently under development.

Rotating wall technique for radial plasma compression. Due to work by the P.I. and collaborators, positron plasmas can be compressed radially inward (i.e., across the magnetic field and opposite to the density gradient) by applying a rotating electric field [14-17]. This technique provides the capability for "infinite" plasma confinement and the ability to tailor plasma density for a particular application.

High magnetic field storage trap. An existing, high-magnetic-field (5 tesla), cryogenic, positron trap [12], shown in Fig. 3, was used for the research. The outward diffusion and rotating-wall compression produce plasma heating that is mitigated by cyclotron cooling in the 5-tesla magnetic field (cooling time ~ 0.1 sec.). Tests were done with electrons, due to the higher available fluxes and the fact that single component electron plasmas behave the same from a plasma point of view as single- component positron plasmas. In the positron phase of the work, positrons plasmas from the buffer-gas trap will be "stacked" in the high-field trap on a several minute cycle time to achieve $\geq 10^{10}$ positrons in a single plasma cell (shown as the open black oval in Fig. 2). [Note that here and elsewhere in this report, a "cell" is a single-component plasma in an individual Penning-Malmberg trap in the case where more than one such plasma are arranged in a single electrode structure.]

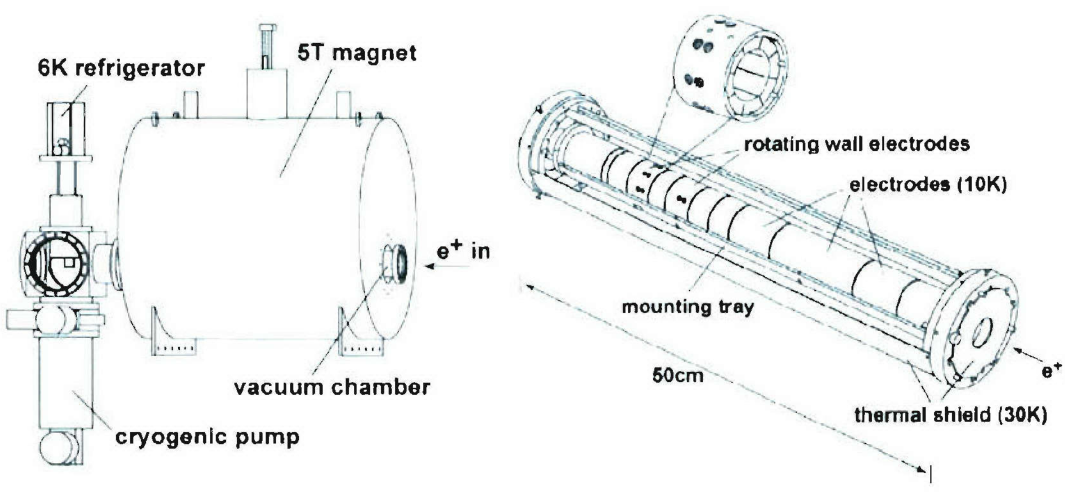

Fig. 3. Overview of the existing high-field trap (left) and the trap electrode structure (right) that were used for the research reported here.

Diagnostics. A number of diagnostic techniques were used to characterize the single-component plasmas, including 2D CCD images of radial density profiles and measurements of total particle number, N_{tot}, plasma length, L, and plasma temperature, T, by studying the characteristics of the plasma modes.

The apparatus and techniques described above provide the following capabilities:

- Excellent plasma compression without tuning to plasma modes
- Very high-density plasmas ($n \geq 3 \times 10^{10}$ cm $^{-3}$)
- High-density plasma confinement for days

2.2 Design and operation of a multicell trap

In order to maximize antimatter plasma confinement and storage capacity, the P. I. and collaborators invented a novel design of multicell Penning trap, shown in Fig. 4 [11]. This design is central to the goal of the project described here. The large space charge potential of large numbers of positrons is mitigated by dividing the plasma into *m*, rod-shaped plasmas of length *L*, each oriented along the magnetic field [e.g., in a hexagonal-close-packed (HCP) arrangement transverse to the field] and shielded from each other by close-fitting copper electrodes. Thus, for a given maximum electrical potential *V* applied to the electrodes, the number of stored positrons can be increased by a factor of *m*. In

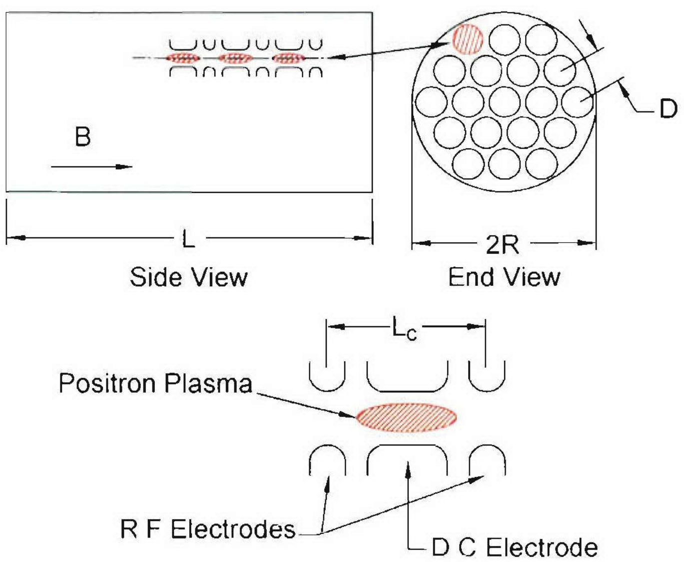

Fig. 4. Schematic diagram of a 95-cell trap, showing the arrangement of cells parallel and perpendicular to *B*. The research reported here verified key concepts assumed in this design. This device consists of 19, hexagonally close-packed cells perpendicular to the magnetic field and 5 in-line cells in the field direction. The design parameters for this device, to be built in follow-on work, are summarized in Table I.

Table I. Design parameters of a 95-cell, multicell trap for 10^{12} positrons.

Number of cells ($m \times p$ = 19 x 5)	**95**
Total positron number, N (10^{12})	**> 1**
Positrons per cell N_C (10^{10})	**> 1**
Magnetic field (T)	**5**
Electrode length, L (cm)	**50**
Electrode diameter, $2R$ (cm)	**7.5**
Confinement voltage, V_c (kV)	**1.0**
Cell spacing (cm) D	**1.7**
L_c	**10**
Plasma density (10^{10} cm^{-3})	**3**
Plasma temperature (eV)	**0.3**
Space charge potential (V)	**750**
Rotating wall frequency (MHz)	**10**

addition, the design breaks up each long rod of plasma into p separate plasmas in the direction along the magnetic field (i.e., separated by electrodes at potential V_c). The plasma length is decreased by a factor L/p. This reduces the effects of (off-axis) magnetic nonuniformities and outward, asymmetry-driven radial transport during the filling and compression cycles. Design parameters for a full 95-cell multicell trap are summarized in Table I. The electrode structure will be cooled to cryogenic temperatures, to ensure a high-quality vacuum environment. Positron loss is expected to be small on the design-goal time scale of weeks.

One important issue, not addressed in the first multicell design, was the method that would be used to fill the off-magnetic-axis cells. In addition to verifying the design-goal confinement capacity of a single cell, the work reported here developed new technology to accomplish this task. The solution, namely filling off-axis cells by a new technique, developed during the course of the work, is described below. The performance of this technique has surpassed expectations and has proven to be an excellent method to fulfill this objective.

2.3 Challenges addressed by the work reported here

Achieving the project goals described above required overcoming major obstacles:

(i) Large space charge potentials. For large particle numbers, N, the space charge potential of a cylindrical, single-component plasma of length, L, in a Penning-Malmberg trap is proportional to N/L. Thus for fixed L, the number, N, of particles that can be stored is limited by the maximum potential that can be applied to electrodes (i.e., in vacuum, in the presence of the plasma). In the work reported here, the working confinement potential was increased from 100 to 1,000 V. This permitted increasing the maximum particle number in a single plasma cell from 3×10^9 to 3×10^{10}. The design in Table I is likely conservative in this regard. If one could work with ~ 3 kV, for example, a trap for 10^{12} positrons would require only 24 cells - alternatively, the 95 cell trap could confine 3×10^{12} positrons.

(ii) Off-axis fill, store and retrieval. Conventional trapping techniques *were not* capable of meeting the project goals. As described below, this required the development of new techniques to move plasma rapidly across the magnetic field. A novel method to accomplish this was successfully tested in the work described here. It involves use of a dynamic state of the plasma that allows the plasma to be moved radially and rotate about the magnetic axis. The radial position of the plasma is changed in a controlled way by suitable application of a rotating electric field. This technique was validated in the present phase of the project. It will be used to transfer plasma into, and out of off-axis cells. Transfer times are estimated to be ≤ 1 ms, and so that a 100-cell trap can be emptied in ≤ 0.1 s.

The results reported here have addressed these challenges. In addition to these accomplishments, experiments were successfully completed to operate two plasma cells simultaneously and a new electrode structure was designed for the next phase of the work.

3. Tasks Proposed for This Project

Following are the specific task statements from the proposal. Of the tasks listed, all except item 6 were planned to be, and were, conducted with electron plasmas for increased data rate.

1. *Demonstrate the ability to work with 1 kV electrode potentials.*
2. *Increase single plasma-cell storage capacity to 1 x 10^{10} particles in a single cell.*
3. *Develop protocols to operate two plasma cells simultaneously.*
4. *Develop a method to move plasmas off the magnetic axis by 1 cm in a 5 T field and phased transfer out of this trapping region.*
5. *Design a new electrode structure to test operation of off-magnetic-axis plasma cells.*
6. *As time permits, demonstrate efficient positron plasma transfer and stacking in the high-field trap.*

All of the promised tasks 1 – 5, inclusive, were accomplished. The sixth, optional, task was not completed, but a new positron source for this purpose was installed and benchmarked. It will be used for the completion of this task.

4. Description of the Experiments

The experiments were performed in a cylindrical Penning-Malmberg trap, shown schematically in Fig. 1. Electron plasmas are injected using a standard electron gun and are confined radially by an applied 5 tesla magnetic field, with axial confinement provided by voltages applied to the end electrodes. Rotating electric fields were applied to the plasma using a special-purpose, four-phase rf generator attached to a four-segment

electrode. Each segment extends 90^o azimuthally; combined, they produce a radial electric field with azimuthal mode number $m_\theta = 1$ rotating in the same direction as the plasma.

The trap is operated in "inject-manipulate-dump" cycles that exhibit very good shot-to-shot reproducibility. Dumped electron plasmas are accelerated to about +5 kV before striking a phosphor screen, with the resulting images recorded by a CCD camera. This z-integrated profile and the trap geometry are used to calculate the plasma length and plasma density. Typical values of plasma space charge, ϕ_0, ranged from 10 V to 990 V. The parallel plasma temperature, $T_{||}$, was measured by slowly lowering the confinement voltage and measuring the escaping charge [18].

The plasma is cooled by cyclotron radiation in the 5T magnetic field at a rate Γ_c = $(1/T)(dT/dt) \sim 6\ s^{-1}$ [19], which is fast compared to the compression and expansion time. Thus, in most cases, the plasmas were found to remain relatively cool (i.e. $T \leq 0.2$ eV; $T/ e\phi_0 << 1$), even in the presence of strong RW fields.

After the plasma is injected into the trap, the RW field was turned on with amplitude V_{RW}, and frequency f_{RW}. The evolution of the plasma was studied by repeating the experiment for different hold times. The plasma reaches a steady-state after a few seconds. Experiments on longer time scales have shown that this steady-state density *can be maintained for more than 24 hours.* Initially, in steady-state, and in expansion after the RW is turned off, the plasma profiles are close to that of a rigid-rotor (i.e., constant-density), except slightly broadened at larger radii.

5. Accomplishment of the Proposed Tasks

In the following, accomplishments are related to the specific tasks listed above.

5.1. Demonstrate the ability to work with 1 kV electrode potentials.

Special programmable 1 kV power supplies were designed and built for this purpose. Good performance of the system was achieved at the 1 kV design goal for a variety of electrode configurations. Based upon this experience we believe we can operate at even higher values of electrode potential.

5.2. Increase single plasma-cell storage capacity to 1 x 10^{10} particles in a single cell.

Using the power supplies described in task 5.1, plasmas were created and confined using a 1.0 kV confinement potential for three different plasma lengths, 5.1, 10.2 and 20.3 cm. Data for a variety of plasma lengths and fill voltages are summarized in Table I. The maximum space charge potential, ϕ_0, was 990 Volts (i.e., representing a net excess confinement potential of only 10 V). The maximum plasma density was 6.2 x 10^{10} cm^{-3}. The dependence of plasma density on N_{tot} for three different confinement lengths, L_c is illustrated in Fig. 5(a), and the dependence of N_{tot} on L_c for the three different filling voltages, V_f, is illustrated in Fig. 5(b). Note that three of the cases exceed the N_{tot} = 1 x 10^{10} particle design goal. ***Plasmas with total numbers of particles up to 3.3 x 10^{10} were created, which is a factor of 3 above the stated goal.***

Table I. Summary of plasma parameters achieved for a 1.0 kV confinement potential, including the confinement length L_c, fill voltage V_f, total particle number N_t, plasma radius R_p, plasma length, L_p, plasma density $\bar{n}$, and the space charge potential ϕ_o.

L_c (cm)	V_f (V)	N_t (10^{10})	R_p (mm)	L_p (cm)	$\bar{n}$ (10^{10} cm^{-3})	ϕ_0 (V)
5.08	300	0.18	1.8	4.7	0.38	270
	600	0.42	1.0	5.5	2.4	670
	900	0.70	0.7	7.3	6.2	930
10.2	300	0.42	1.8	9.8	0.42	300
	600	0.91	1.1	10.8	2.2	715
	900	1.60	0.9	14.7	4.3	990
20.3	300	0.90	1.8	20.0	0.44	320
	600	1.90	1.9	20.6	0.81	640
	900	3.30	1.9	23.4	1.2	975

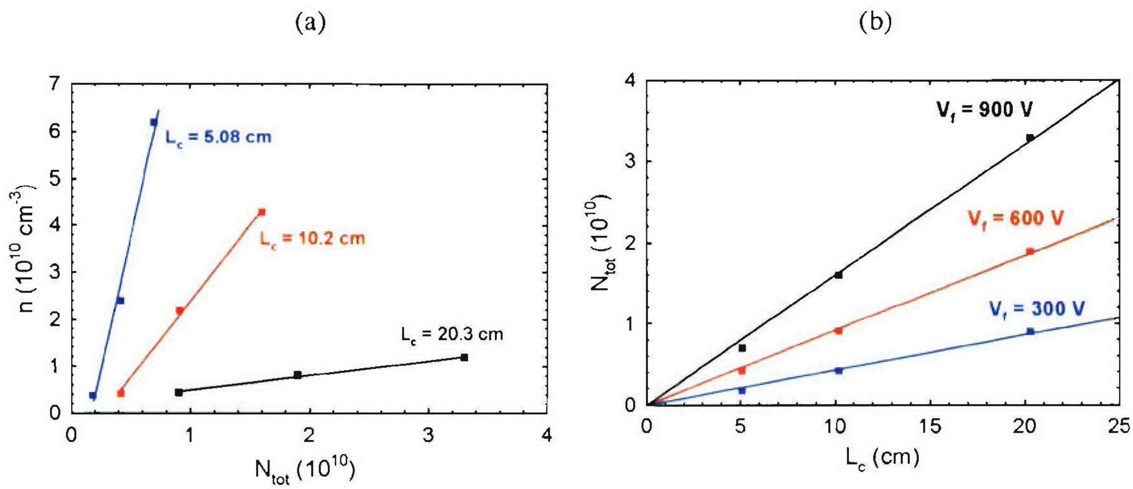

Figure 5. (a) The dependence of plasma density on N_{tot} for three different confinement lengths L_c; and (b) the dependence of N_{tot} on L_c for three different fill voltages, V_f, with all using a confinement voltage, Vc = 1.0 kV.

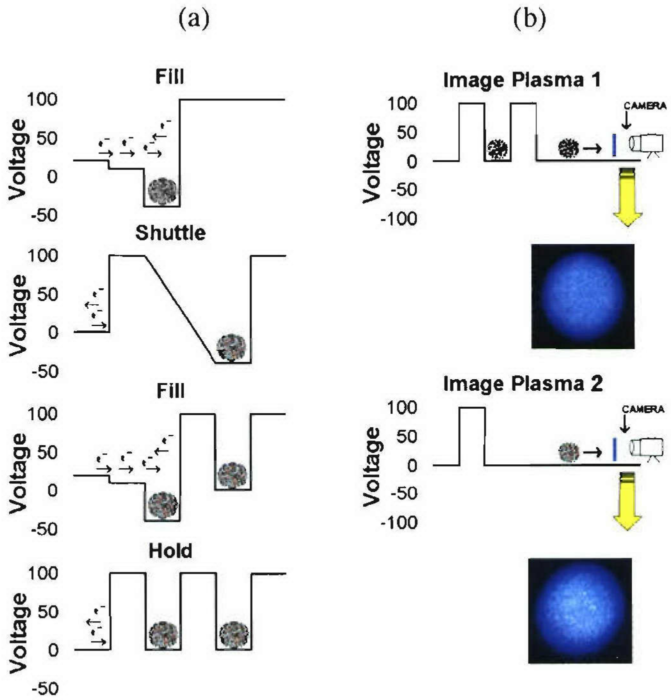

Fig. 6. (a) Schematic diagram of the potential profile during the sequential filling of two plasma cells with electron plasma; and (b) the sequential dumping of these plasmas and the resulting images.

5.3. Develop protocols to operate two plasma cells simultaneously.

As illustrated in Fig. 6, two plasmas were loaded in two separate cells of the high-field Penning-Malmberg trap using a "fill-shuttle-fill- hold" protocol. Following this "hold" stage, independent control of the plasmas was demonstrated by individually "dumping" them onto a phosphor screen where they could be imaged.

Each plasma consisted of $N \approx 5.5 \times 10^8$ electrons. The plasmas were 10 cm long, 0.93 mm in radius, and separated axially by 10 cm. It was confirmed that there was no increase in outward radial transport with the addition of the second plasma to the trap. The plasmas were confined for 30 seconds with no noticeable expansion. Additional studies are planned to investigate confinement of these multi-cell trapped plasmas on longer time scales.

5.4. Development of a method to move plasmas off the magnetic axis by 1 cm in a 5 T field and phased transfer out of this trapping region.

Our approach to tasks 5.4 and 5.5 was novel. It entailed the invention of a new method to move plasma across a magnetic field. In order to protect this intellectual property, a Patent Disclosure for this invention has been filed with the U. S. Patent Office by the UCSD Technology Transfer Office. The invention involves excitation of a so-called "diocotron" mode of the plasma and use of this mode to move plasmas across the

magnetic field. The diocotron mode is an off-axis displacement of a plasma of a single sign of charge confined in a cylindrical electrode in a Penning-Malmberg trap. A key feature of this invention is the exploitation of the fact that the frequency of this mode increases monotonically with the displacement, D, of the plasma from the center of the electrode. The $m_\theta=1$, $k_z = 0$, diocotron mode is a simple displacement of the plasma column from the trap axis. The frequency of oscillation of this mode is given by $f_D \approx (R_p/R_w)^2 f_E|1 + (D/R_w)^2|^{-1}$, where f_E is the plasma $\boldsymbol{E \times B}$ rotation frequency, R_p is the plasma radius, and R_w is the inner radius of the confining electrode. This mode can be excited by applying a sinusoidal signal at frequency f_D. By locking to the applied signal, we can dump the plasma at any phase of oscillation. Note that the frequency depends also on the plasma displacement, D. Thus, by exciting different frequency diocotron modes, we can achieve any off-axis displacement. The plasma mode becomes "autoresonant," meaning that, within some locking range, the amplitude of the mode self-adjusts so that the plasma is in tune with the applied frequency [20].

Figure 7 shows schematically the autoresonant response of the plasma to a constant amplitude sine wave as the frequency of the applied sine wave is changed. The final displacement is set by the final frequency of the wave, and the phase angle in the plane perpendicular to the cylindrical axis is set by the phase of the sine wave. Thus measurement of the phase and frequency of the drive signal, $V_D(\omega)$ accurately determines the position of the plasma in the plane perpendicular to the magnetic axis.

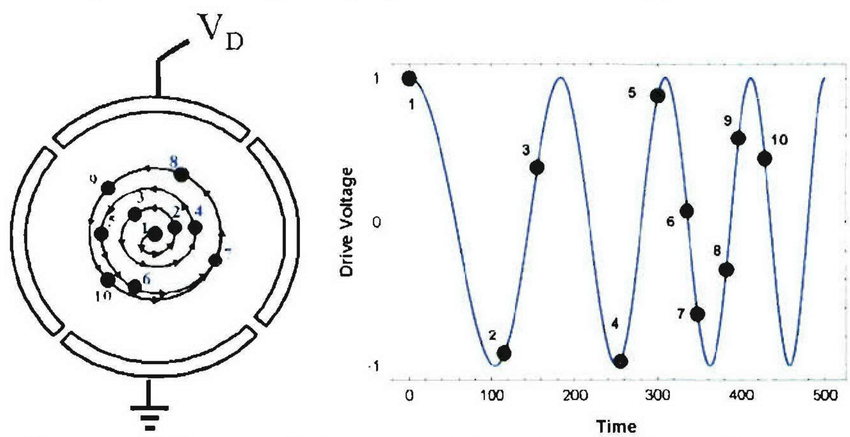

Fig. 7. Conceptual diagram of plasma evolution when nonlinear diocotron mode is excited by the drive voltage, $V_D(\omega)$, shown, which is applied to one segment of the rotating wall electrode. The solid circles are plasma (left) positions in the electrode structure as would be measured when the plasma is dumped; and (right) corresponding phase of the applied drive signal. The numbers correlate specific positions of the plasma location and drive signal in the two plots. Note that as the frequency of the drive increases, the plasma column moves to larger displacement.

This concept was tested in a series of experiments. The radial profiles of plasmas were measured using a CCD camera, after the particles are accelerated to 8 kV and dumped on a phosphor screen. Figure 8 shows images for several amplitudes of applied signal for plasmas that have been dumped at a fixed phase, $\phi = 0^\circ$, with respect to the drive. For each image, the measured displacement, D, from the trap axis is indicated. Note that, for these experiments, the maximum viewable displacement on the screen is about 0.45 cm,

while $R_w = 1.27$ cm.

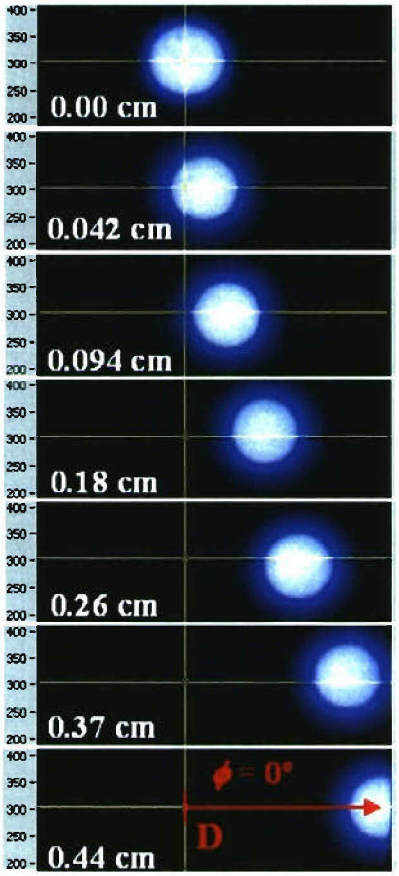

Fig. 8. Plasma images for different values, D, of off-axis displacement. All plasmas are dumped with phase $\phi = 0°$. Note that the plasma extent and shape remains approximately the same, independent of D.

The diocotron mode frequency and amplitude are measured on a separate receiver electrode after the drive signal is turned off. This received signal can be decomposed into a sum of sinusoidal harmonics, with the amplitude, V_n, of the n^{th} harmonic given by $V_n = A_n D^n$, where D is the plasma displacement, and the A_n are known coefficients related to the receiver electrode dimensions and the electrical circuit impedance. Thus the displacement, D, is proportional to V_1 (i.e., the amplitude of the fundamental frequency component of the signal) namely $D = V_1/A_1$; and also, $D = (A_1/A_2)(V_2/V_1)$, where the latter expression is independent of the receiver amplifier gain. Figure 8 shows the measured displacement, as measured using the ratio V_2/V_1, for different excitation levels V_1, verifying these relationships.

We can directly image dumped plasmas out to $D \approx 0.45$ cm. For $D \leq 0.45$ cm, the displacements measured from these CCD images are also plotted in Fig. 9. The comparison indicates very good agreement (i.e., $\leq \pm 10\%$) between the two

measurements. This confirms our ability to detect large displacements using measurements of the amplitude of the excited diocotron mode. As shown by the circled point in Fig. 9, *the goal of producing a 1 cm displacement from the axis has been achieved.* It is also noteworthy that this represents a displacement out to 79% of the electrode radius. This has important, positive, implications for the ability to fill an electrode structure with multicell plasmas at a high packing fraction.

Figure 10 shows the CCD images as the phase of the excitation is changed from $\phi = 0°$, 90°, 180°, 270°, all at a fixed displacement $D \approx 0.26$ cm. This verifies the ability to transfer the plasma out of the confinement region at different azimuthal phases. We are currently devising a technique to nonlinearly phase-lock the plasma to the external drive, which will allow for arbitrary control of the phase. Combined with the amplitude control, this will allow for the ability to arbitrarily dump the plasma at any location in the plane perpendicular to the magnetic field.

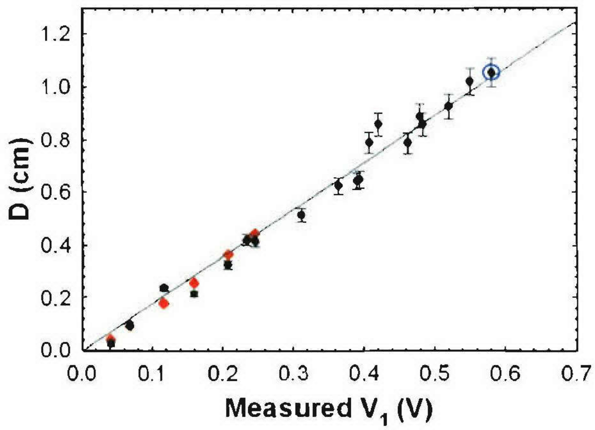

Fig. 9. (•) Displacement, D, for fixed phase, $\phi = 0°$, from measurement of the harmonic ratio, V_2/V_1, plotted as a function of the amplitude, V_1, of the fundamental frequency. For comparison, (♦) show the displacements as measured directly from images on the phosphor screen. The circled point corresponds to a displacement of 1 cm, which is 80% of the wall radius.

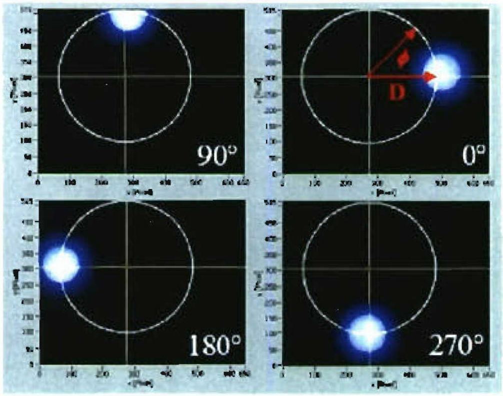

Fig. 10. Plasma images for different phase angles, ϕ, for $D \approx 0.26$ cm. [The image at $\phi = 90°$ is clipped due to the limited extent of the phosphor screen.]

Figure 11 illustrates how this autoresonant diocotron-mode excitation technique will be used to fill a multicell positron trap.

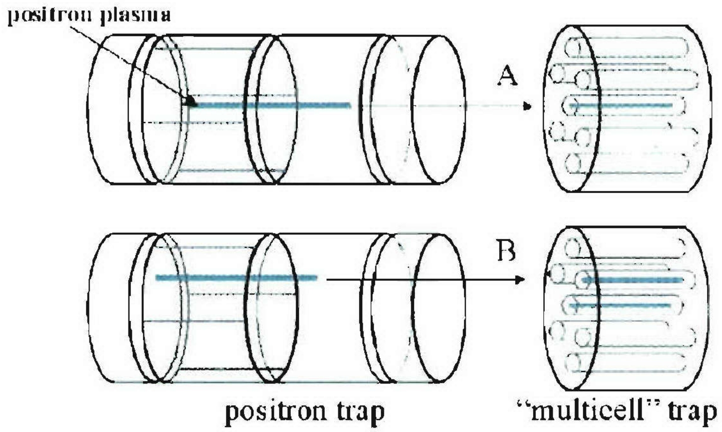

Fig. 11. Illustration of use of the autoresonant diocotron mode technique to inject positrons into specific cells in a "multicell" trap. In A, the positron plasma is kept on-axis and injected into the center "cell." In B, the plasma is excited to the necessary displacement and phase-dumped for injection into the desired, off-axis plasma cell. Use of such a multi-cell trap enables a factor of ten or more increase in positron storage capacity and thus represents a very important step towards a practical, portable multicell antimatter trap.

5.5. Design a new electrode structure to test operation of off-magnetic-axis plasma cells.

As shown in section Fig. 4 above, the design and operation of the multicell trap relies on the ability to inject, trap, and store plasmas in individual cells spaced both axially and radially in the common vacuum chamber and magnetic field. Section 5.3 presented experiments that demonstrated trapping and storage in two independent, axially separated cells located along the magnetic axis. In order to complete the design for the full multi-cell trap, a new electrode structure must be constructed in order to optimize the ability to trap and store plasmas in cells that are displaced radially from the magnetic axis. It is also desirable to check the confinement properties of plasmas in cells located axially near the ends of the electrode structure. These locations are displaced from the mid-plane of the superconducting magnet and, consequently, will have non-negligible radial magnetic field components that can affect plasma stability and confinement.

In considering possible designs for this electrode structure, the eventual goal of using a HCP arrangement transverse to the field was used to determine the radial and azimuthal location of the individual traps. The design incorporates several different cell diameters in order to determine the minimum cross-field size for an individual cell and hence make the multicell trap as compact as possible. Finally, as described in section 5.4, in order to fill and empty off-axis cells, a specially designed arrangement of "feed" electrodes is also necessary.

The final design of the test structure is shown in Fig. 10, and a cut-away view is shown in Fig. 11. The structure is composed of two sections, an arrangement of large-diameter "feed" electrodes, and another arrangement of small-diameter "storage" electrodes. The "feed" section, illustrated in Fig. 12(a), is composed of an arrangement of large diameter electrodes that will be used to move the plasma off-axis and phase locked dumping to inject into the various storage cells. This procedure will be reversed to empty cells along the magnetic axis for end use.

The storage section is composed of five individual electrode packages, each package composed of two axially separated cells, as shown in 12 (b). Of the five storage electrode packages, four will be located off the magnetic axis, and two of those will have different cell diameters, as indicated in Fig. 12 (b). The storage electrodes will be contained in a copper structure (solid black in Figs. 10 and 11). This structure will be used to support the different packages, as well as to allow space for the necessary co-axial connections (not shown). As indicated in Fig. 10 (b), the radial and azimuthal location of the electrode stacks all correspond to specific locations in the eventual HCP arrangement. The total "storage" section will thus be composed of 10 individual cells, with the capacity to store > 10^{11} particles. Off-axis cells near the end of the electrode structure will be used to study the effects of magnetic fringe fields, described above.

To fill the multicell test structure, the buffer-gas positron accumulator (from section 2.1) will be used to deliver small positron bunches to the "feed" structure. The technique described in Section 5.4 will be used to move each bunch to the given radial and azimuthal locations of a storage cell. After filling the first axial cell at each location, the technique described in Section 5.3 will be used to move plasmas axially to the adjacent, in-line cell, and hence to allow the re-filling of the first cell, similar to the procedure shown in Fig. 6.

Experiments with this test structure are expected to demonstrate all of the techniques and procedures necessary for the successful operation of a multicell trap. This will allow for the final design of a multicell trap capable of accumulating and confining more than 10^{12} positrons, and an important first step toward a portable antimatter trap.

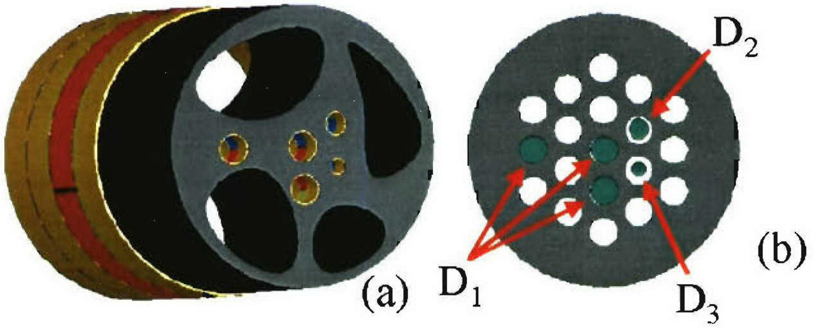

Fig. 10. (a) 3D rendition of the test electrode design; and (b) end view, showing the placement of the off-axis cells (shown in green) relative to the ultimate HCP design. Cell diameters are: D_1 = 25 mm, D_2 = 18 mm, and D_3 = 12 mm.

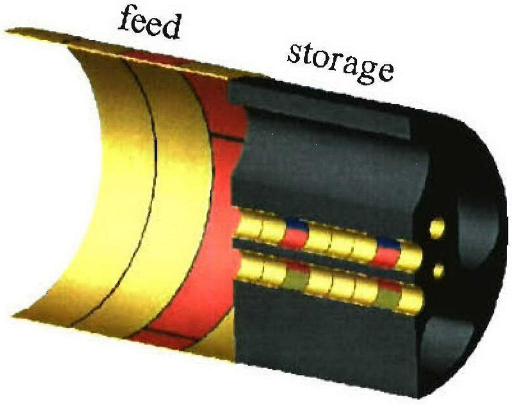

Figure 11. View of the electrode structure showing cut-away views of the feed (and extraction) electrodes and two of the storage-electrode packages.

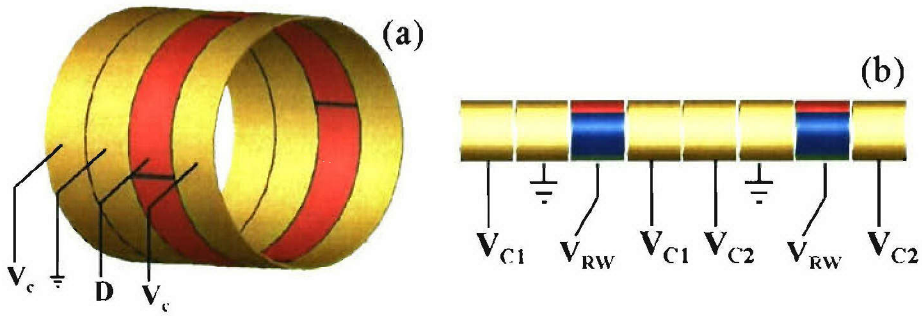

Fig. 12. Views of the (a) feed and extraction electrodes, where V_c is the confinement and control voltage, and D is the segmented electrode for diocotron-mode control; (b) schematic of a storage-electrode package with two plasma cells. V_{C1}, V_{C2} are the confinement and control voltages for the respective cells, and V_{RW} are the rotating-wall electrodes for plasma compression and enhanced confinement.

5.6. As time permits, demonstrate efficient positron plasma transfer and stacking in the high-field trap.

This task was proposed as optional only. We opted not to undertake it in *lieu* of additional work to learn how to move plasmas off axis. We believed that more work on this latter task would serve the project better in the long run. However, a new 50 mCi ^{22}Na radioactive source for the positron stacking work has been installed and tested. It is operating up to specifications, producing 7 x 10^6 slow positrons per second. This positron flux is comparable to the best ever observed in our laboratory (i.e., positrons per mCi) over 15 years of testing similar sources. This source will be used to complete Task 5.6.

6. Summary of Accomplishments During the Present Grant

All of the five tasks proposed for this project have been completed successfully. The goals of two of the most critical of these tasks have been exceeded. Multicell operation has been demonstrated. Phased control of the off-axis excitation of plasmas to a displacement radius of 1 cm and phased dumping of off-axis plasmas have also been demonstrated with a precision that exceeded expectations. Operation of the trap with confinement potentials of 1 kV has been demonstrated. Confinement of 3×10^{10} particles in a single cell has also been demonstrated, exceeding the proposed goal by a factor of three. Finally, design of the electrode structure for the next phase of the work was also completed.

A Patent Disclosure has been filed for the invention described in Sec. 5.4. An abstract has been submitted for a talk at the 2006 Workshop on Nonneutral Plasmas on this work, and a technical paper is being prepared and will be submitted for publication reporting the technical progress made in this phase of the project.

7. The Future of the Multicell, Antimatter Positron Trap

As illustrated in Fig. 2, in 1989 the record number of positrons accumulated efficiently was $N \sim 10^4$. We expect to accumulate 10^{10} in a single cell within the next year. Further progress requires a new approach – the development of the multicell trap described here. This research will increase the number of trapped positrons to $N \geq 10^{12}$; and with further multiplexing, additional orders of magnitude are possible. A proposal to complete the design, construction, and testing of a multicell trap for $> 10^{12}$ positrons is described briefly in Appendix I.

The availability of this large number of positrons opens up many new possibilities, such as providing bursts of positrons far larger than available by any other means. Applications of large pulses of positrons include improved methods to create low-energy antihydrogen, creation of Bose-condensed positronium atoms (i.e., the first step toward a gamma-ray laser), and study of electron-positron plasmas.

The successful development of the multicell trap will be a major step toward creation of a versatile *portable* antimatter trap. While portable traps have been discussed previously [2, 21, 22], none have yet been developed. Portable traps can be expected to be important for the many applications where use of radioactive and/or accelerator-based positron sources present significant difficulties, such as in the characterization of materials for electronic chip manufacture, operation in a satellite, or on a ship.

While the present design calls for a superconducting magnet and cryogens or a refrigerator, it could be made to fit in a volume of only a few cubic meters and transported in a vehicle the size of an SUV. More important in the long run, the knowledge base developed as a result of the project is very likely to lead to much more compact designs with many fewer logistic requirements.

The goals of this project are conservative and there is a high probability of success. Related to this, there is a rapid learning curve associated with the underlying science and

technology. Thus, it is likely that further improvements in design can be made in real time during the course of the work, including increasing storage capacity and confinement time and decreasing the weight and size of the multicell trap apparatus.

8. References

1. Jean, P., Knodlseder, J., Lonjou, V., *et al.*, Early Spi/Integral Measurements of 511 Kev Line Emission from the 4th Quadrant of the Galaxy, *Astro. and Astrophys.* **407**, L55, 2003.
2. Surko, C. M. and Greaves, R. G., Emerging Science and Technology of Antimatter Plasmas and Trap-Based Beams, *Phys. Plasmas* **11**, 2333, 2004.
3. Amoretti, M., Amsler, C., Bonomi, G., *et al.*, Production and Detection of Cold Antihydrogen Atoms, *Nature* **419**, 456, 2002.
4. Gabrielse, G., Bowden, N., Oxley, P., *et al.*, Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States, *Phys. Rev. Lett.* **89**, 213401, 2002.
5. Schultz, P. J. and Lynn, K. G., Interaction of Positrons Beams with Surfaces, Thin Films, and Interfaces, *Rev. Mod. Phys.* **60**, 701, 1988.
6. in *New Directions in Antimatter Chemistry and Physics*, edited by C. M. Surko and F. A. Gianturco (Kluwer Academic Publishers, The Netherlands, 2001).
7. Mills, A. P., Jr., Positronium Molecule Formation, Bose-Einstein Condensation and Stimulated Annihilation, *Nucl. Instrum. Methods B* **192**, 107, 2002.
8. Driscoll, C. F. and Malmberg, J. H., Length-Dependent Containment of a Pure Electron-Plasma Column, *Phys. Rev. Lett.* **50**, 167, 1983.
9. Driscoll, C. F., Fine, K. S., and Malmberg, J. H., Reduction of Radial Losses in a Pure Electron Plasma, *Phys. Fluids* **29**, 2015, 1986.
10. O'Neil, T. M., *Phys. Fluids* **26**, 2128, 1983.
11. Surko, C. M. and Greaves, R. G., A Multi-Cell Trap to Confine Large Numbers of Positrons, *Rad. Chem. and Phys.* **68**, 419, 2003.
12. Danielson, J. R., Schmidt, P., Sullivan, J. P., *et al.*, in *Non-Neutral Plasma Physics V, a Cryogenic, High-Field Trap for Large Positron Plasmas and Cold Beams (Aip Conf. Proc. #692)*, edited by e. a. M. Schauer (American Institute of Physics Press, Melville, NY, 2003), p. 149.
13. Greaves, R. G. and Surko, C. M., Antimatter Plasmas and Antihydrogen, *Phys. Plasmas* **4**, 1528, 1997.
14. Greaves, R. G. and Surko, C. M., Inward Transport and Compression of a Positron Plasma by a Rotating Electric Field, *Phys. Rev. Lett.* **85**, 1883, 2000.
15. Greaves, R. G. and Surko, C. M., Radial Compression and Inward Transport of Positron Plasmas Using a Rotating Electric Field, *Phys. Plasmas* **8**, 1879, 2001.
16. Danielson, J. R. and Surko, C. M., Torque-Balanced High-Density Steady States of Single Component Plasmas, *Phys. Rev. Lett.* **95**, 035001, 2005.
17. Danielson, J. R. and Surko, C. M., Radial Compression and Torque-Balanced Steady States of Single-Component Plasmas in Penning-Malmberg Traps, *Phys. Plasmas*, in press, 2006.

18. Eggleston, D. L., Driscoll, C. F., Beck, B. R., *et al.*, Parallel Energy Analyzer for Pure Electron Plasma Devices, *Phys. of Fluids B* **4**, 3432, 1992.
19. Beck, B. R., Fajans, J., and Malmberg, J. H., Measurement of Collisional Anisotropic Temperature Relaxation in a Strongly Magnetized Pure Electron Plasma, *Phys. Rev. Lett.* **68**, 317, 1992.
20. Fajans, J., Gilson, E., and Friedland, L., The Effect of Damping on Autoresonant (nonstationary) Excitation, *Phys. Plasmas* **8**, 423, 2001.
21. Tseng, C. H. and Gabrielse, G., Portable Trap Carries Particles 5000 Kilometers, *Hyperfine Inter.* **76**, 381, 1993.
22. Lewis, R. A., Smith, G. A., and Howe, S. D., Antiproton Portable Traps and Medical Applications, *Hyperfine Inter.* **109**, 155, 1997.

Appendix I. Proposed plan to complete the design, construction and testing of a trap for 10^{12} positrons in two phases, Options 1 and 2.

Following is a plan to complete the multicell positron trap for 10^{12} particles that follows closely the one outlined in the original DARPA proposal. Schedule and budget could be adjusted to accommodate changes in constraints and goals.

Option 1 (15 months duration; proposed estimated cost, $ 370 K). This Option will complete the preparatory R & D necessary before designing and building a multicell trap for 10^{12} positrons. Both electron and positron plasmas will be used in this phase of the work. While mostly using existing equipment, a new test electrode structure will be constructed and used to establish the ability to operate off-axis plasma cells. This Option will also include demonstration of transfer and stacking of 1×10^{10} positrons in a single cell in the high-field trap and the conceptual design of the electrode structure for the 10^{12}-positron multicell trap. Success with each of these items constitutes a separate deliverable.

Option 2. (36 months; proposed estimated total cost $2.4 M including approximately $1.05 M in hardware). The tasks completed in this phase of the project and Option 1 will provide a multicell trap for 10^{12} positrons. Option 2 will include the design and construction of a stand-alone high-magnetic-field, multicell trap for long-term positron storage, including hardware, control and diagnostic systems, and protocols and software for accumulation, storage and dumping plasmas. It will result in a complete, stand-alone system, including positron source, buffer-gas accumulator and high-field storage trap. While each of the tasks listed above constitutes a separate deliverable, the ultimate deliverable will be the entire system with demonstrated ability to accumulate $N = 1 \times 10^{12}$ positrons, store them for times in excess of 1 week, and reproducibly provide selected amounts of stored positron plasma for a range of end uses.